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VISIBLE AND INFRARED TRANSMISSION THROUGH SNOW

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By

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Visible and infrared extinction in falling snow is a function of snow particle concentration and snow crystal size and shape. Relationships between existing meteorological conditions and these characteristics have been investigated using measurements made during the SNOW-ONE Field Experiment. Effects of meteorological conditions upon extinction are discussed and empirical models are suggested. Causes of the variation of extinction with wavelength in the visible and infrared are identified and the magnitudes of some of the possible effects are estimated.

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INTRODUCTION

The transmission of visible and infrared electromagnetic radiation through the atmosphere is of concern to developers and users of electro-optical devices, particularly during conditions of low visibility. Falling snow creates such conditions over large parts of the earth's surface and during a fairly large percentage of the time during winter months in some areas. For example, falling snow occurs about 12 percent of the time during the observation period in the Uplands of West Germany in February.

A recent review by Mason[1] conveys the nature and complexity of the problem of relating transmission through falling snow to meteorological conditions. Figure 1 and table 1 summarize the results of several investigators relating visible extinction coefficient, β_{VIS}, to precipitation rate, R (equivalent liquid water). It can be seen for example, that the extinction coefficient may vary by a factor of five for a fixed precipitation rate. The variation in these results for snow is due to variations in the snow crystal types and characteristic sizes. The curve labeled R is for rainfall and shows that the extinction coefficient for snow may be more than an order of magnitude greater than that for rain for equivalent precipitation rate.

SIMPLE OPTICAL MODEL FOR SNOW

In general, the extinction coefficient β_λ at wavelength λ for an ensemble of N aerosol particles of cross-sectional area A is given by

$$\beta_\lambda = \int_A N(A) Q_{ext}(n,A,\lambda) A dA \tag{1}$$

where Q_{ext} = extinction efficiency, n = complex index of refraction. According to the conservation of mass, the mass of the snow crystals per unit area accumulating on the ground per unit time equals the mass of the equivalent liquid water per unit area per unit time, or

$$\rho_{water} R = \rho_{ice} \int_V N(V) v(V) V dV \tag{2}$$

where ρ = density

V = particle volume

v = particle settling velocity.

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[1]Mason, J. B., "Light Attenuation in Falling Snow," ASL-TR-0018, US Army Atmospheric Sciences Laboratory, White Sands Missile Range, NM, 1978.

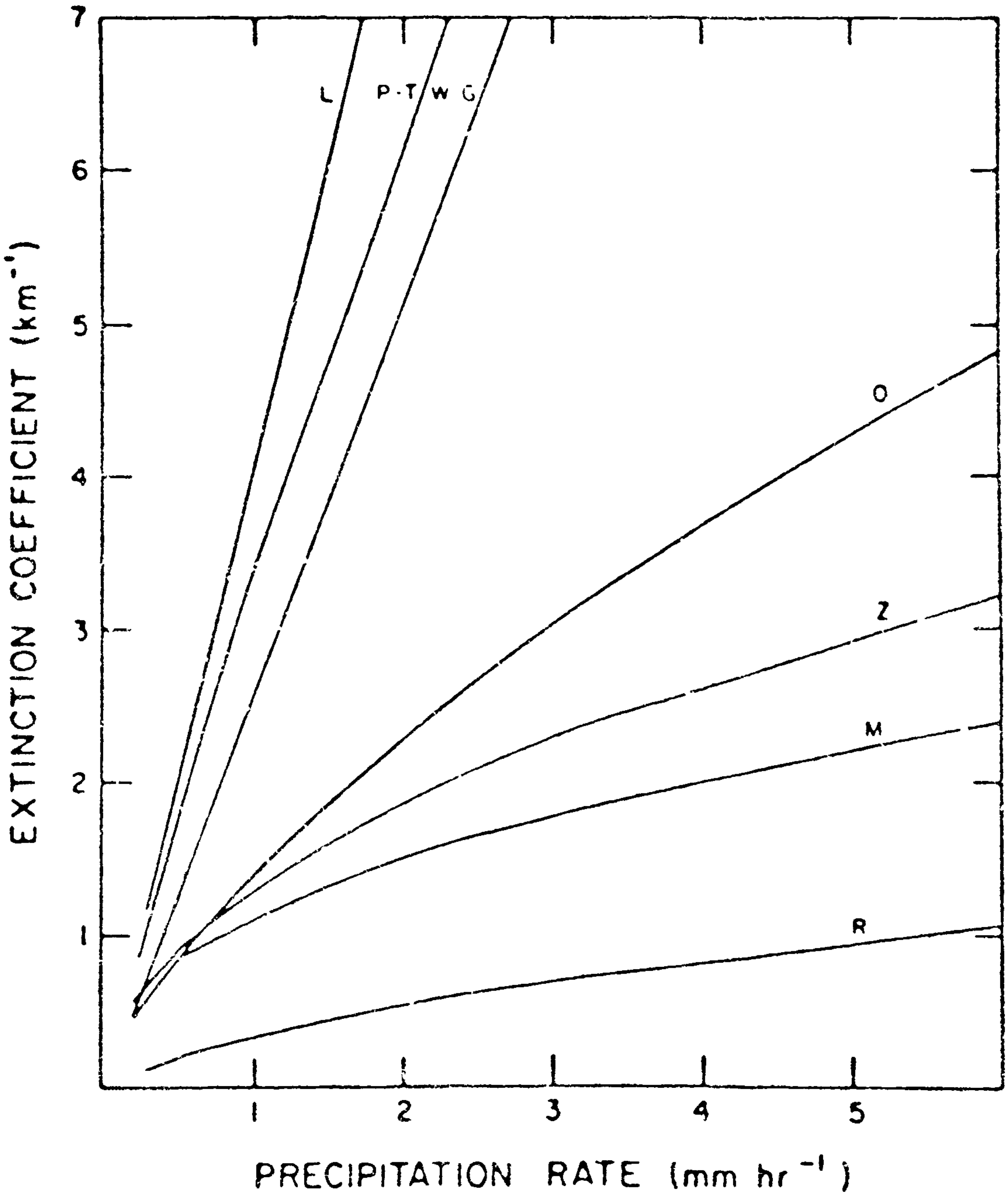

Figure 1. Empirical correlations for extinction coefficient vs snowfall precipitation rate (from Mason[1]). The letters indicate the various investigators as given in table 1.

TABLE 1. CORRELATIONS OF FALLING SNOW EXTINCTION COEFFICIENT (km^{-1}) VS ACCUMULATION RATE ($mm\ h^{-1}$) (MASON[1])

Investigator	Correlation
Lillesaeter[2]	$\beta_{VIS} = 3.93R$
Zel'manovich[3]	$\beta_{VIS} = 1.3R^{0.5}$
Polyakow & Treljakov[4]	$\beta_{VIS} = 3.2R^{0.91}$
Mellor[5]	$\beta_{VIS} = 1.11R^{0.42}$
Warner & Gunn[6]	$\beta_{VIS} = 2.53R$
O'Brien[7]	$\beta_{VIS} = 1.393R^{0.69}$

Then, combining (1) and (2)

$$\beta_\lambda = \frac{\rho_{water}}{\rho_{ice}} \frac{R\int N(A)Q_{ext}(n,A,\lambda)AdA}{\int N(V)v(V)VdV} . \qquad (3)$$

This may be simplified by assuming that the particles are homogeneous and monodispersed, and that the geometrical optics approximation is valid (Q_{ext} = 2), which is the case when the particles are sufficiently large compared to λ.

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[1]Mason, J. B., "Light Attenuation in Falling Snow," ASL-TR-0018, US Army Atmospheric Sciences Laboratory, White Sands Missile Range, NM, 1978.

[2]Lillesaeter, O., "Parallel-Beam Attenuation of Light, Particularly by Falling Snow," J Appl Meteorol, 4:607, 1965.

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[4]Polyakova, E. A., and V. D. Tretjakov, "Visibility in Falling Snow," Trudy Glavnoy Geophysics Obs, Leningrad, 100:53, 1960.

[5]Mellor, M., "Light Scattering and Particle Aggregation in Snow Storms," RR193, US Army Cold Regions Research and Engineering Laboratory, Hanover, NH, 1966.

[6]Warner, C., and K. L. S. Gunn, "Measurement of Snowfall by Optical Attenuation," J Appl Meteorol, 8:110, 1969.

[7]O'Brien, H. W., "Visibility and Light Attenuation in Falling Snow," J Appl Meteorol, 9:671, 1970.

Then

$$\beta_{VIS} = \beta_{IR} = 2.2 \frac{R}{V} \frac{A}{V} . \qquad (4)$$

Note that particle volume concentration $\kappa = \frac{R}{V}$. Then by assuming various crystal shapes with characteristic sizes and settling velocities, one may derive interrelationships of the form

$$\beta_{VIS} = CR \qquad (5)$$

where C is a constant. For small needle-shaped crystals the relationship is similar to that of Lillesaeter.[2] Larger plate-like crystals will yield a smaller extinction coefficient with a relationship closer to that of Mellor[5] or Zel'manovich.[3]

Since $\frac{A}{V}$ is inversely proportional to some characteristic crystal dimension d, that is $\frac{A}{V} \approx \frac{1}{d}$, one can easily see that for fixed precipitation rate, extinction decreases as crystal size increases. Since crystal size tends to increase with increasing temperature or relative humidity because of increased agglomeration, extinction should decrease in these c .ditions. However, it should be noted that these results are based on snow occurring alone and that if fog occurs simultaneously, as is often the case, then additional complications arise.

SNOW-ONE DATA

The Scenario Normalization for Operation in Winter - Obscuration and the Natural Environment (SNOW-ONE) Field Experiment was the first of a series of winter exercises conducted by the US Army Corps of Engineers for the purpose of collecting data used to investigate the effects of snow on the propagation of electromagnetic energy. Visible, infrared, and near-millimeter wave transmission measurements were made over a path length of 0.65 km through

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[2]Lillesaeter, O., "Parallel-Beam Attenuation of Light, Particularly by Falling Snow," J Appl Meteorol, 4:607, 1965.

[5]Mellor, M., "Light Scattering and Particle Aggregation in Snow Storms," RR193, US Army Cold Regions Research and Engineering Laboratory, Hanover, NH, 1966.

[3]Zel'manovich, I. L., "Microstructure and Transmittance of Snowfall," Trudy Glavnoy Geophysics Obs, Leningrad, 100:58, 1960.

falling snow concurrently with measurements of meteorological conditions, snow particle size distributions, shape characteristics and concentration. These measurements were made at Camp Ethan Allen near Burlington, Vermont, during the period 5 Jan 81 through 20 Feb 81. Data were collected during periods of falling snow on nine days during this time frame and have been documented by Redfield.[8] Figure 2 shows transmittances at three wavelengths as measured with Barnes transmissometers on 22 Jan 81. Light snow, light snow with fog, and snow flurries occurred on that day with observed visibilities of 1 to 8 km.

EMPIRICAL MODEL FROM SNOW-ONE DATA

A set of 181 data points from five of the days during which snow occurred was used to derive a regression equation relating extinction to meteorological parameters. These data show that the visible extinction coefficient, $\beta_{0.55}$, increases as volume concentration increases and decreases with both increasing surface temperature and relative humidity. The resulting regression equation is

$$\frac{\beta_{0.55}}{\kappa} = 0.0233 - 0.0031\kappa - 0.0101T + 0.0019H \qquad (6)$$

where κ = volume concentration in units of $10^{-8}\,m^3/m^3$

T = surface temperature (°C)

and H = surface relative humidity (%)

Figure 3 shows comparisons between predicted visible extinction coefficients and those derived from the actual transmittances. Comparisons between th actual measured transmittances and those predicted by equation (6) are given in figure 4. These figures show only those data points used in the derivation of equation (6).

[8]Redfield, R. K., "SNOW-ONE Preliminary Data Report," US Army Cold Regions Research and Engineering Laboratory, Hanover, NH, 1981.

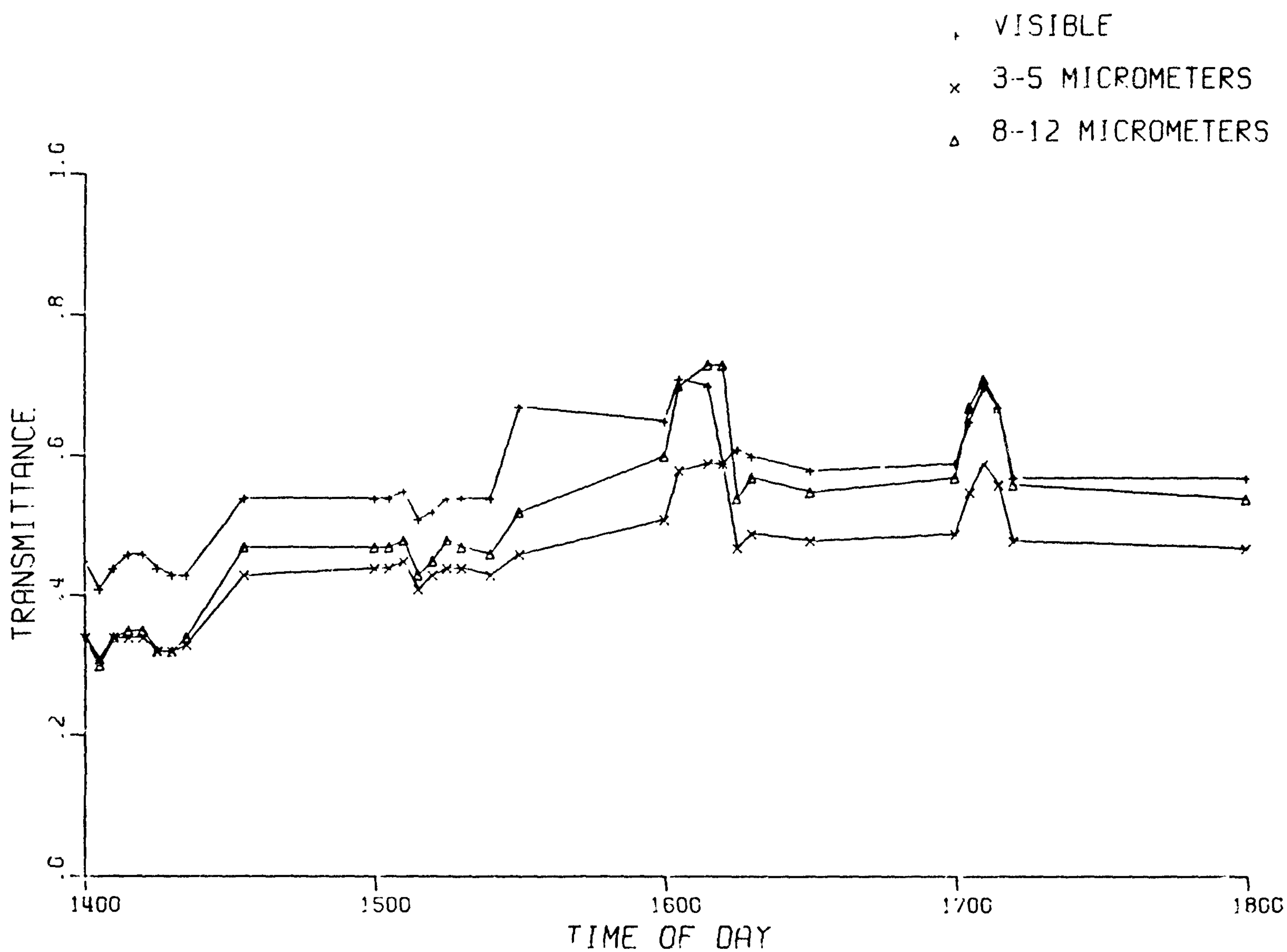

Figure 2. Transmittances measured during SNOW-ONE, 22 Jan 81.

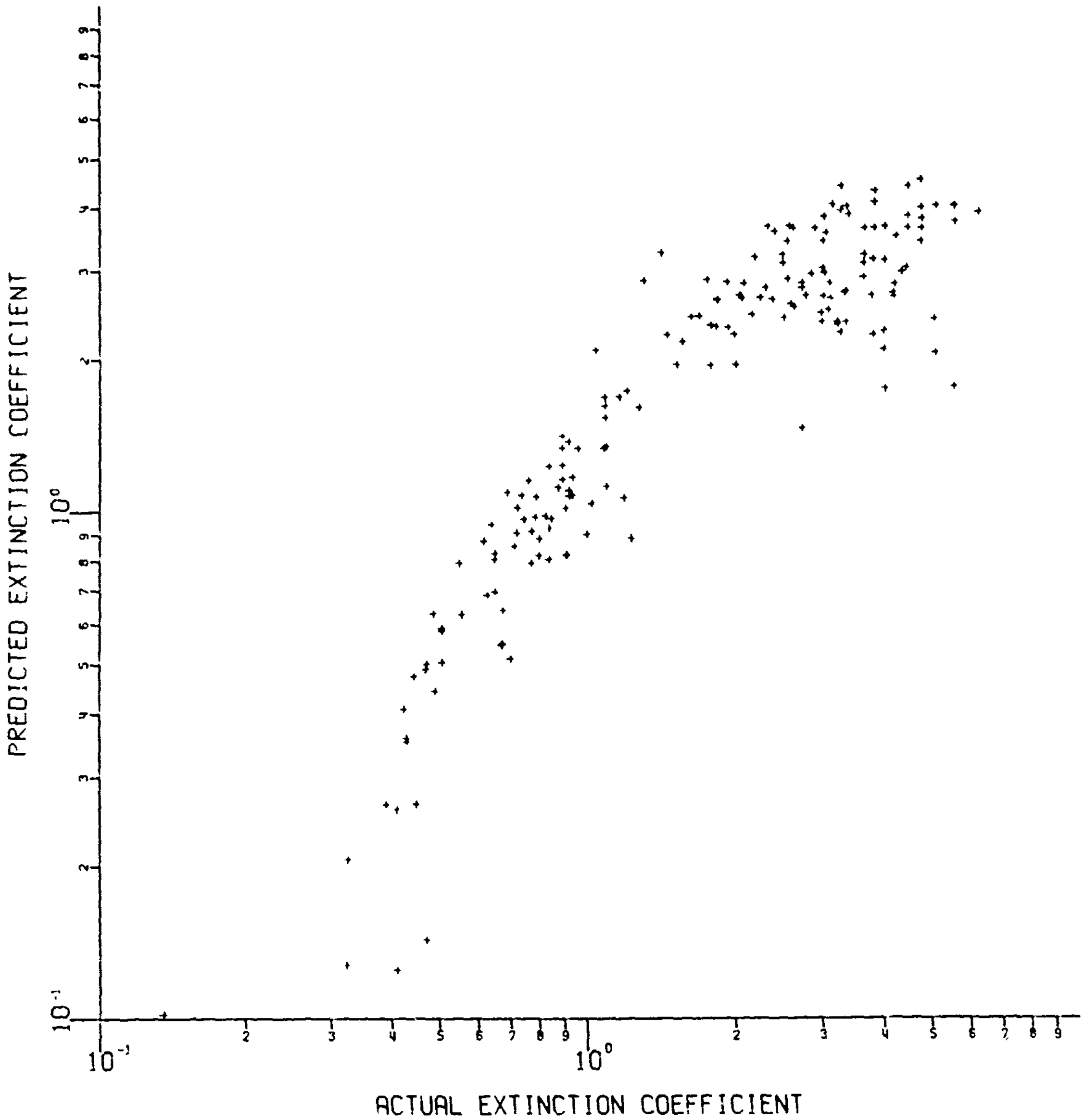

Figure 3. Comparison between visible extinction coefficients from SNOW-ONE measurements and those predicted by equation (6).

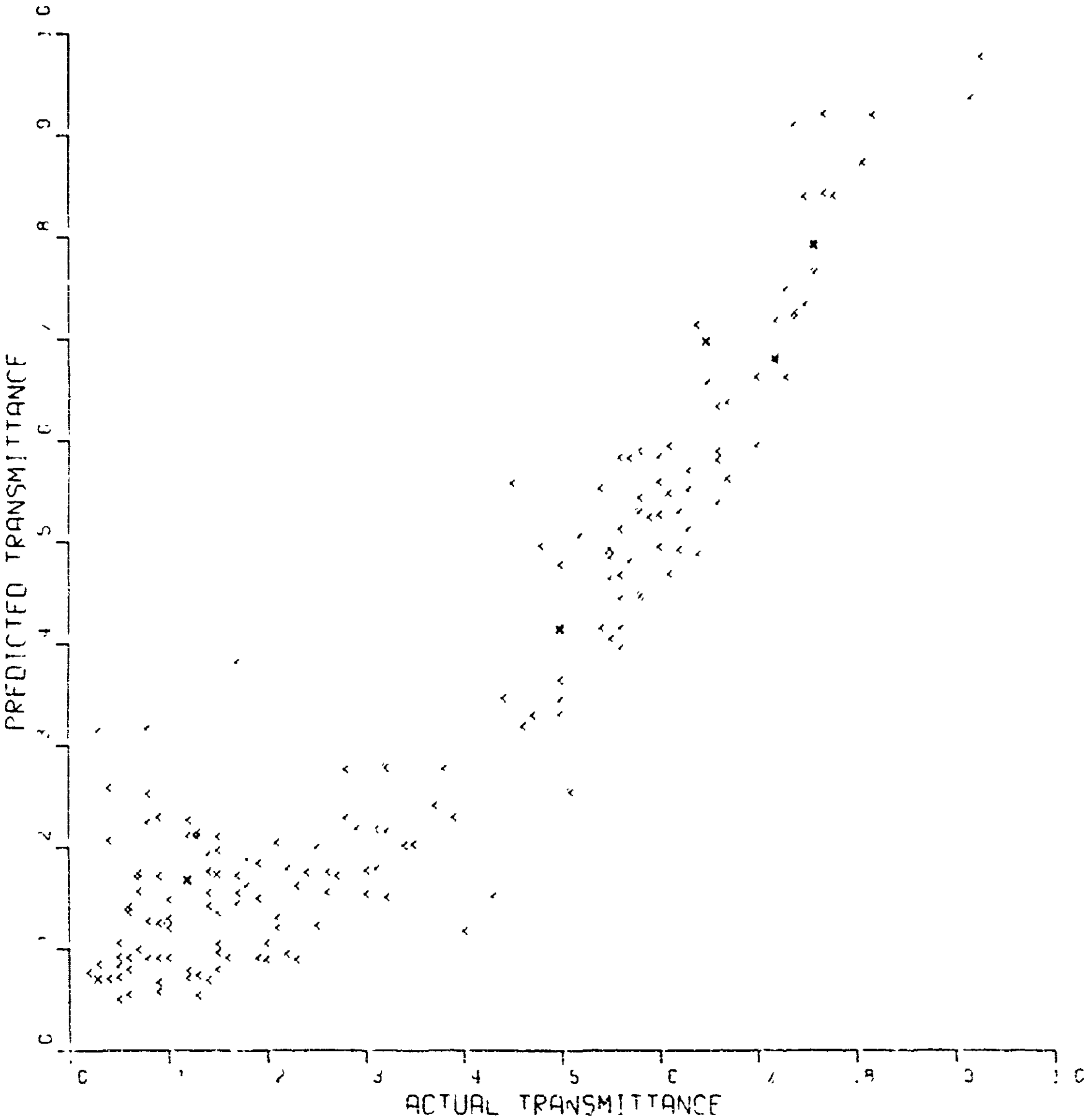

Figure 4. Comparison between visible transmittances measured during SNOW-ONE and those predicted by equation (6).

EXTINCTION WAVELENGTH DEPENDENCE

A number of investigators[9, 10, 11, 12, 13, 14] have measured visible and infrared transmittance through snow of various types. Results of their findings in the 8μm to 12μm and visible regions are summarized in table 2. They found that, in the absence of coexisting fog, measured transmittance is higher in the visible region of the spectrum than the infrared. However, when fog occurred along with the snow, the wavelength dependence of the meter measured transmittance could be reversed with visible transmittance less than infrared. Analysis of data collected at SNOW-ONE resulted in conclusions similar to those of other investigators. This analysis is demonstrated in figure 5, showing the ratio of the extinction coefficient at 10.4μm to that at 0.55μm for a period of time during a snowstorm at SNOW-ONE. Relative humidity during the same time is also shown. Figure 6 shows a camparable plot for 3.0μm. Preliminary indications are that the discrepancies between the GAP model[11] and actual data at 3.0μm are due to gaseous and aerosol (snowflake) absorption.

Regression analyses were performed on SNOW-ONE data taken during a variety of conditions of snow type, intensity, and meteorological conditions. It was found that when relative humidity is low (less than or equal to 94 percent), the infrared extinction coefficient may be expressed as a function of visible extinction coefficient (or equivalent visibility) only. For larger values of relative humidity (when fog is more likely to occur), the infrared extinction coefficient is a function not only of the visible extinction coefficient, but also temperature and relative humidity. These regression analyses resulted in the following model.

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[9]Bisyarin, V. P., et al, "Attenuation of 10.6μm and 0.63μm Laser Radiation in Atmospheric Precipitation," Radio Engineering and Electronic Physics, 16:1585, 1971.

[10]Gimmestad, E. G., and S. M. Lee, "Infrared Obscuration by Falling and Blowing Snow," Proceedings of National IRIS, 1980.

[11]Sola, M. C., and R. J. Bergeman, "Multi-Spectral Propagation Measurements through Snow," Topical Meeting on Optical Propagation Through Turbulence, Rain and Snow, Boulder, CO, 197 .

[12]Abele, J., H. Raidt, and D. H. Hohn, "Studies on the Influence of Meteorological Parameters on Atmospheric Laser Transmission," Report FFO 1979/20, Forschungsinstitut fur Optik, Tubingen, FRG, 1979.

[13]Chu, T. S., and D. C. Hogg, "Effects of Precipitation on Propagation at 0.63, 3.5, and 10.6 Microns," Bell System Technical Journal, p 723-759, 1968.

[14]Eklund, H., et al, "Atmospheric Transmission Measurements at 10.6μm," Infrared Physics, 18:337-342, 1978.

TABLE 2. INVESTIGATIONS OF TRANSMISSION THROUGH SNOW AT 8μm TO 12μm AND VISIBLE REGION

Investigator/Location	Instrument Type/ Date	Results
Bisyarin, et al[9] RUSSIA	Lasers Jan to Mar 1970	$\beta_{10.6} = 1.38\ \beta_{0.63}$
Gimmestad & Lee[10] Houghton, MI	Transmissometers 17 Mar 1980	$\beta_{8\text{-}12} = 1.25\ \beta_{VIS}^{0.901}$
Sola[11] Fort AP Hill, VA Grafenwohr, FRG	Transmissometers 1975 - 1977	$\beta_{8\text{-}12} = 1.30\ \beta_{VIS}^{0.993}$
Abele, et al[12] Tubingen, FRG	Lasers 12 Dec 1978	Higher transmission at 0.63μm than 10.6μm.
Chu & Hogg[13] Holmdel, NJ	Lasers 1966	10.6μm attenuated more than 0.63μm, no definite wavelength dependence observed
Eklund, et al[14] Goteborg, Sweden	Lasers Mar, Apr 1977	Higher transmission at 0.63μm than 10.6μm except when snow mixed with fog

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[9]Bisyarin, V. P., et al, "Attenuation of 10.6μm and 0.63μm Laser Radiation in Atmospheric Precipitation," Radio Engineering and Electronic Physics, 16:1585, 1971.

[10]Gimmestad, E. G., and S. M. Lee, "Infrared Obscuration by Falling and Blowing Snow," Proceedings of National IRIS, 1980.

[11]Sola, M. C., and R. J. Bergeman, "Multi-Spectral Propagation Measurements through Snow," Topical Meeting on Optical Propagation Through Turbulence, Rain and Snow, Boulder, CO, 1977.

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[14]Eklund, H., et al, "Atmospheric Transmission Measurements at 10.6μm," Infrared Physics, 18:337-342, 1978.

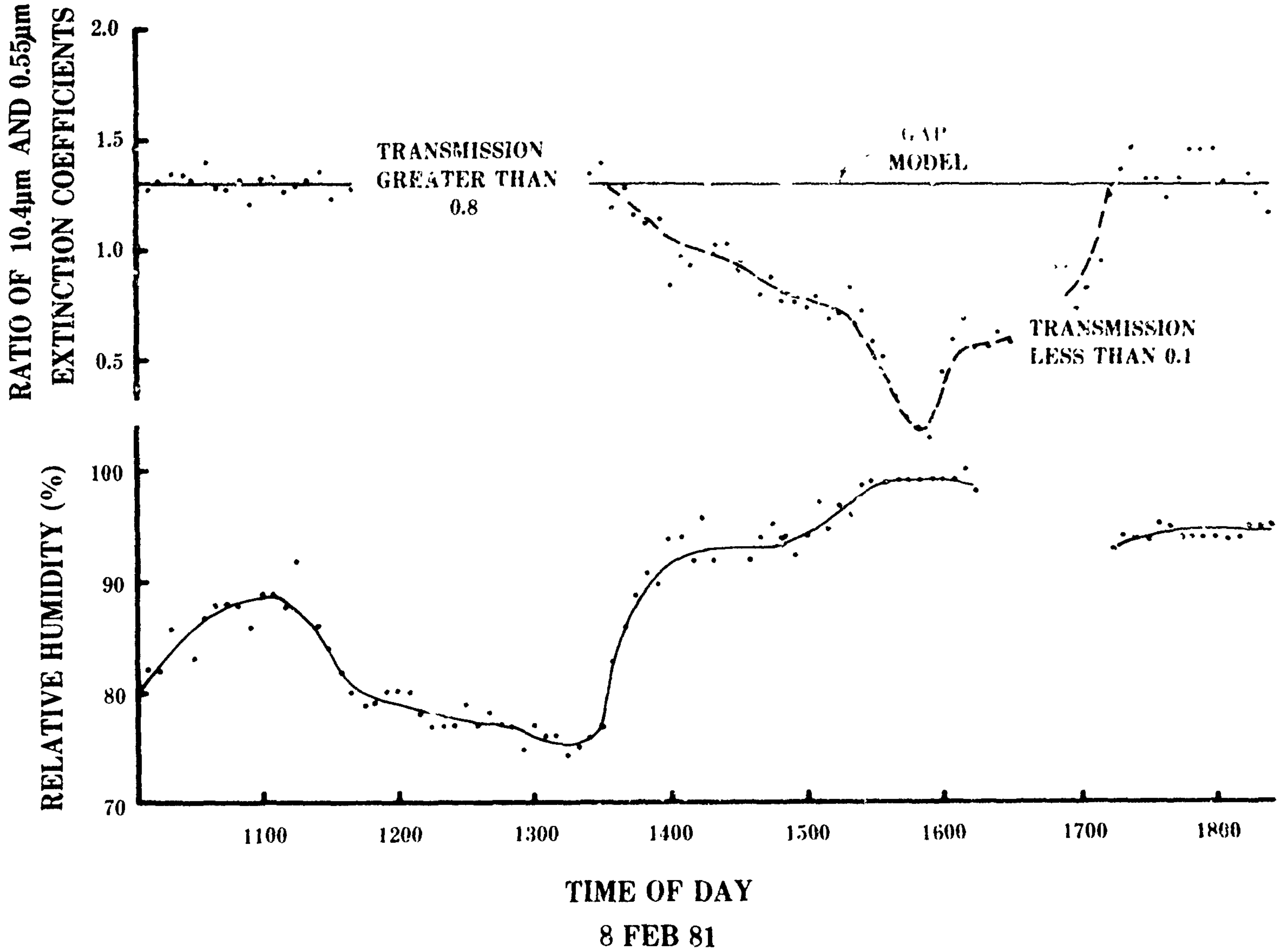

Figure 5. Comparison of extinction coefficients at 10.4μm and 0.55μm during SNOW-ONE. The GAP model of Sola and Bergeman[11] for 8 to 12μm is shown as are corresponding values of relative humidity.

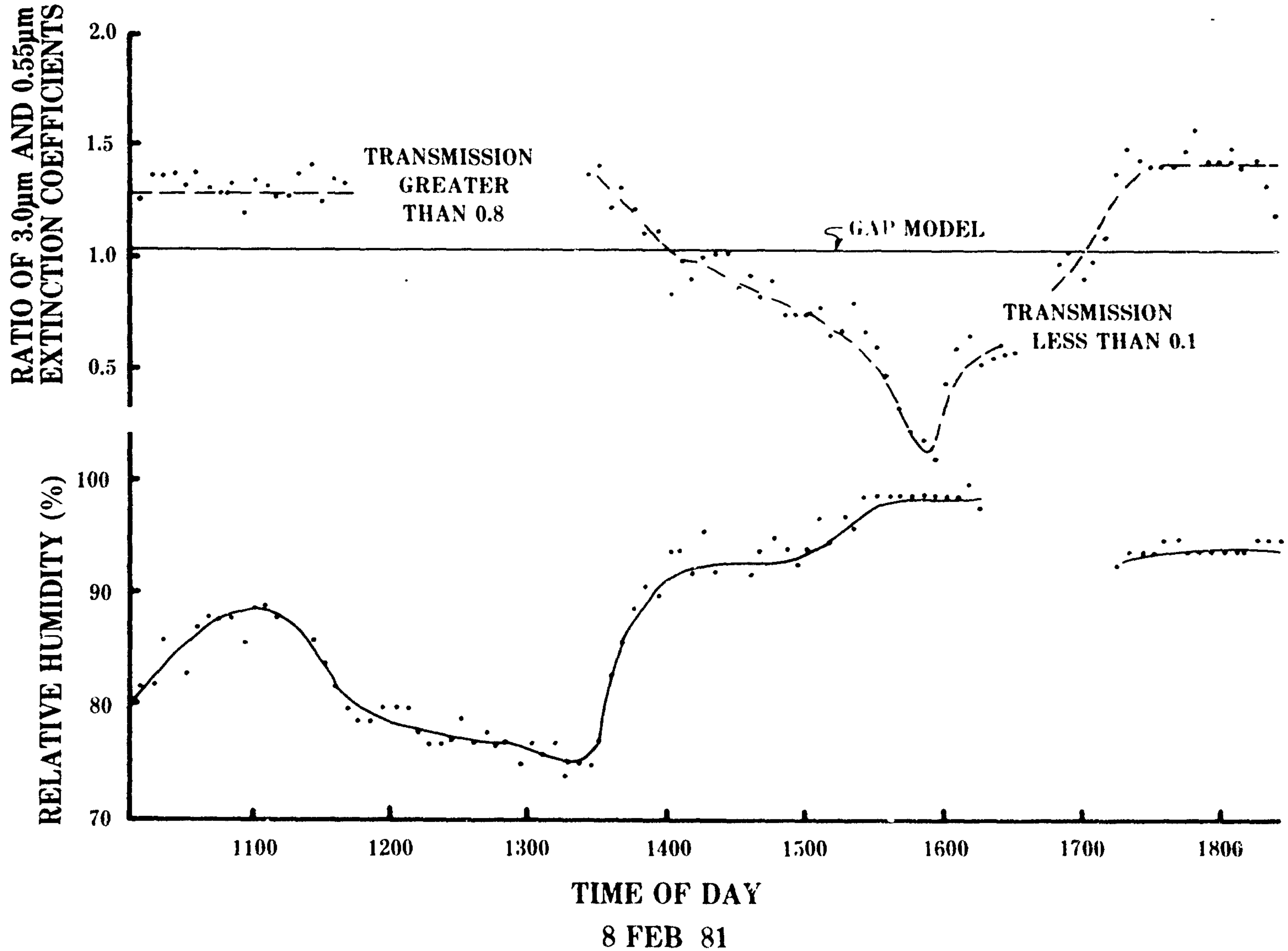

Figure 6. Comparison of extinction coefficients at 3.0µm and 0.55µm during SNOW-ONE. The GAP model of Sola and Bergeman[11] for 3µm to 5µm is shown as are corresponding values of relative humidity.

For transmittance at 3.0μm

$$\beta_{3.0} = 1.21\ \beta_{0.55} \qquad \text{for RH} \leq 94\% \qquad (7a)$$

$$\beta_{3.0} = \beta_{0.55}\ (-0.107\ T - 0.101\ H - 0.042\ V + 10.74) \quad \text{for RH} > 94\% \qquad (7b)$$

and for transmittance at 10.4μm

$$\beta_{10.4} = 1.18\ \beta_{0.55} \qquad \text{for RH} \leq 94\% \qquad (8a)$$

$$\beta_{10.4} = \beta_{0.55}\ (-0.182\ T - 0.223\ H - 0.426\ V + 25.35) \quad \text{for RH} > 94\% \qquad (8b)$$

where

V = visibility (km) = $3.0/\beta_{VIS}$

This model was derived from data with the following ranges and should be used with caution elsewhere.

$1.2\ \text{km} \leq V \leq 7.5\ \text{km}$

$-11.9°C \leq T \leq 2.0°C$

$68\% \leq H < 100\%$

Transmittances predicted by equations (7) and (8) are compared with the corresponding measurements in figures 7 and 8. The model appears to give the largest errors when the relative humidity is between 90 and 95 percent, where the existence of fog is most in doubt, and should be used with caution in this region.

Snowflakes are very large, on the order of 1 mm diameter, compared to visible and infrared wavelengths. Thus, as was indicated in equation (4), the geometrical optics approximation is applicable and, theoretically, extinction should be wavelength independent. As has been seen, however, there are systematic differences in measured transmittances in this wavelength region.

A number of explanations for the reduced infrared extinction compared to visible extinction have been proposed. It appears that several processes combine to give rise to this effect.

(1) When the relative humidity is high, infrared energy is absorbed by the water vapor. However, this effect is small at the cold temperatures at which snow occurs.

(2) Because phase functions for the shorter wavelengths are more sharply peaked in the forward direction, more scattered radiation enters the detector. This effect is difficult to investigate since phase functions for snow crystals are difficult to determine.

(3) While the large-particle (geometrical optics limit) single particle extinction efficiency is the same for visible and infrared wavelengths,

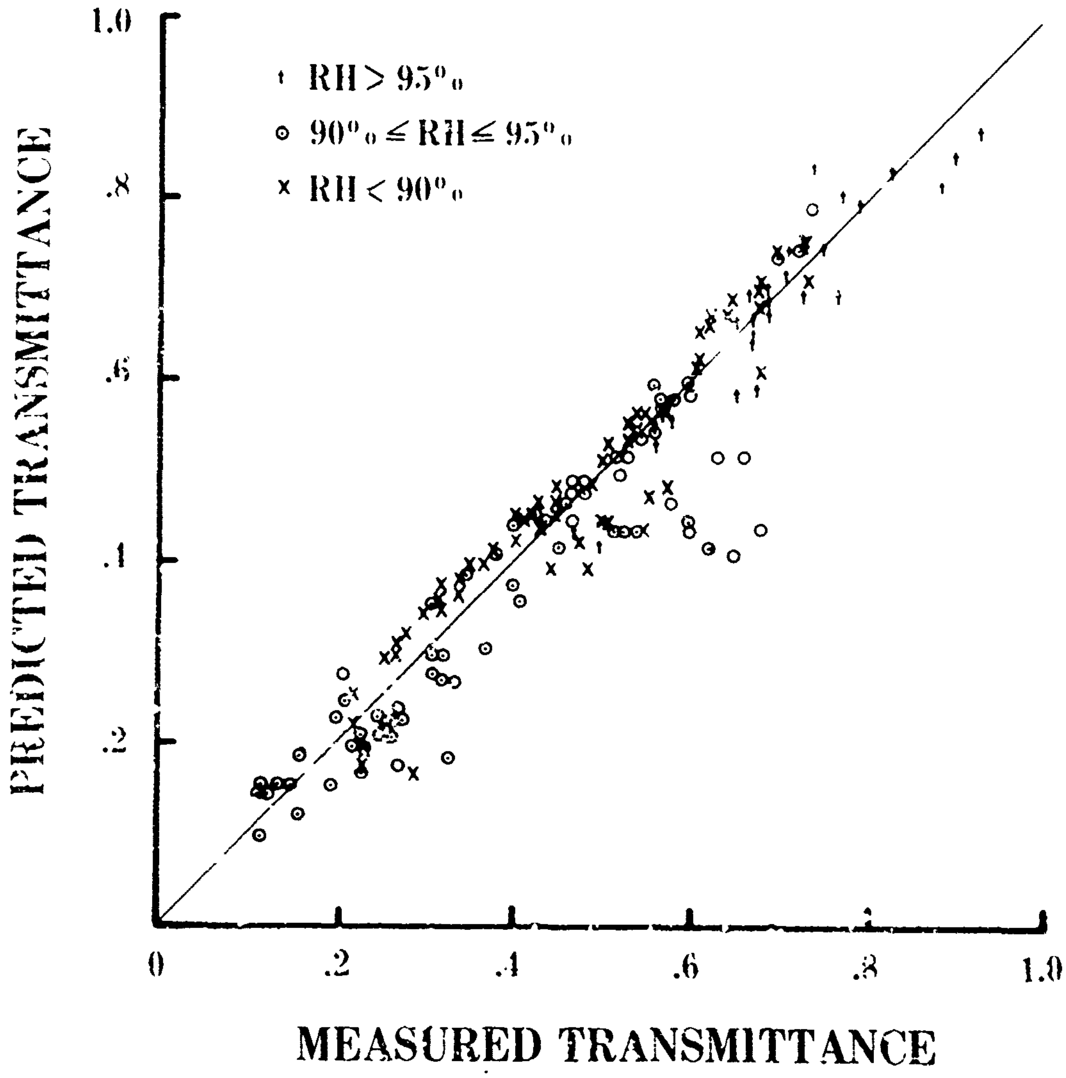

Figure 7. Comparison between 10.4μm transmittances measured during SNOW-ONE and those predicted by equation (8).

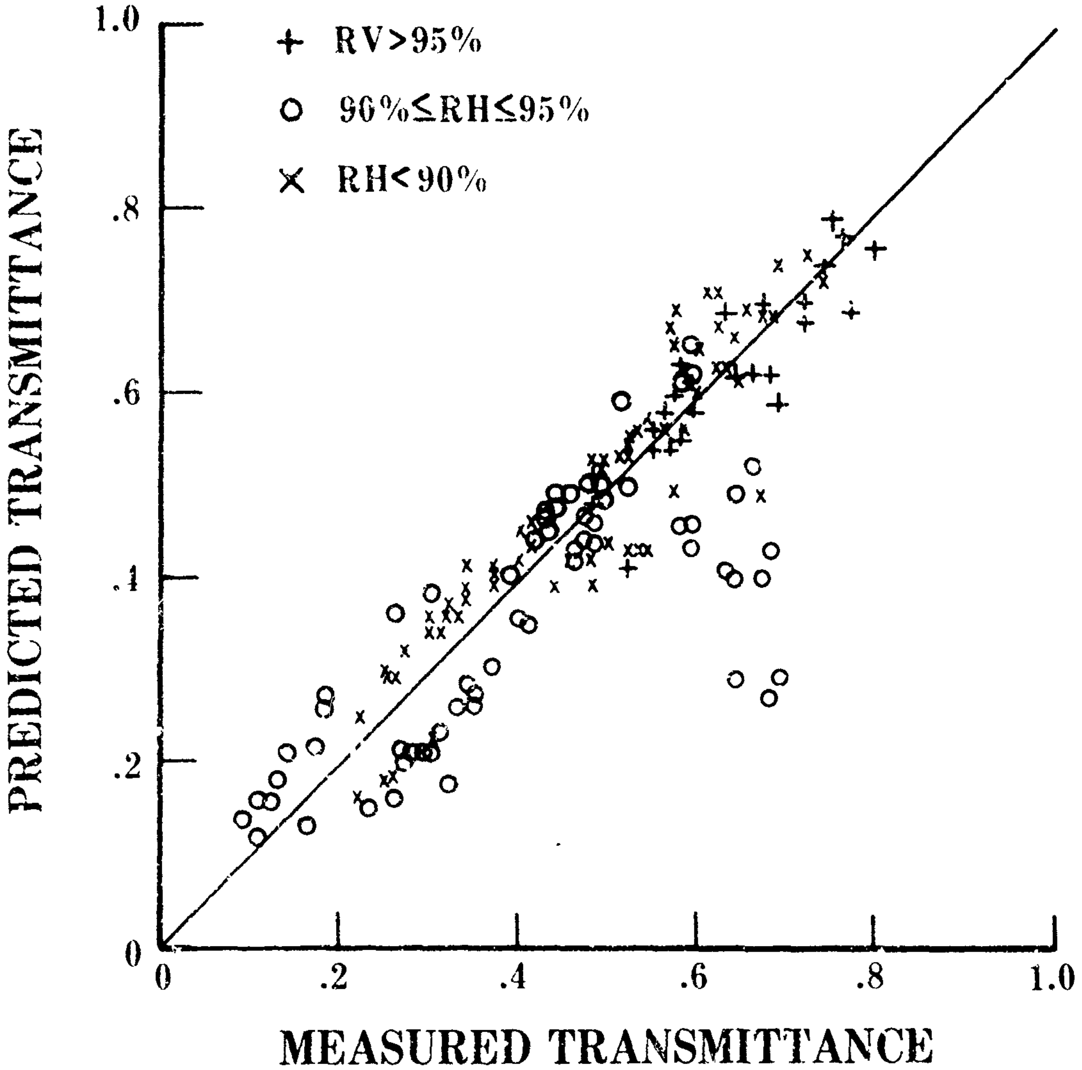

Figure 8. Comparison between 3.0μm transmittances measured during SNOW-ONE and those predicted by equation (7).

essentially all of the visible extinction is due to scattering, while about half of the infrared extinction is due to absorption. This results in more scattered visible energy available to enter the detector.

(4) The visible and infrared differential extinction cross sections due to the presence of fog or low-lying cloud particles may contribute to this effect.

(5) Multiple scattering of visible radiation vs infrared radiation may contribute to apparent differences in measured transmission (assuming the detector collector optics are the same diameter for both wavelengths).

CONCLUSIONS

We have reviewed falling snow obscuration at visible and infrared wavelengths, incorporating both physical and optical aspects of the problem. Using these results, an analysis of falling snow obscuration data obtained during the SNOW-ONE field test has resulted in an empirical model relating visible extinction to snow mass concentration, ambient air temperature, and relative humidity. We then presented a model that relates infrared extinction to visible extinction as a function of visibility, temperature, and relative humidity, with separate equations for high humidity and low humidity. Differences existing between visible and infrared extinction data for falling snow when, from a theoretical viewpoint, no such difference would be expected appear to be due to a combination of processes including water vapor absorption, snow crystal absorption, and multiple scattering effects.

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3. Zel'manovich, I. L., "Microstructure and Transmittance of Snowfall," Trudy Glavnoy Geophysics Obs, Leningrad. 100:58, 1960.

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